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Damage evolution of dynamic characteristics of sandstone under the sequential action of water-rock interaction and cyclic loading and unloading

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Abstract: The rock mass in the hydro-fluctuation belt of the reservoir bank slope is subjected to long-term water-rock interaction and frequent moderate-low intensity reservoir earthquake. The deterioration of the mechanical properties of the rock mass caused by this directly affects the dynamic response and seismic capacity of the reservoir bank slope. Based on this, the settings of the fluctuating zone of the bank slope of the reservoir are simulated, and the water-rock interaction test to simulate the periodic rise and fall of the reservoir water level is designed and carried out. In the course of the test, the cyclic loading and unloading method is used to simulate the influence of seismic action, and the sequential action of water-rock interaction and cyclic loading and unloading is mainly considered. According to the test results, the following conclusions are obtained. (1) The dynamic parameters of the rock sample generally change exponentially from steep to gentle under the water-rock interaction. After considering the sequential action of water-rock interaction and cyclic loading and unloading, the deterioration rate and trend of dynamic parameters of rock samples increase obviously, indicating that frequent moderate-low intensity reservoir earthquakes can obviously promote the damage development of bank slope rock mass in the environment of water-rock interaction for a long time. (2) Under the action of water-rock interaction and cyclic loading and unloading, the microstructure of rock samples gradually loosens from the compacted state, and the corresponding integrity degradation coefficient and the secondary porosity also show a trend of steepness and then slowness. Among them, the microstructure changes of rock samples under the sequential action of periodic water-rock interaction and cyclic loading and unloading are the most significant, followed by the rock samples with initial cyclic loading and unloading damage, and the change of rock samples under the water-rock interaction alone is the smallest. The changes and differences of the microscopic structure of the rock sample under different schemes also govern the degradation law of its dynamic characteristics. (3) Under the long-term water-rock interaction and frequent moderate-low intensity reservoir earthquakes, the internal damage of the reservoir bank slope will gradually accumulate and develop, which will directly affect the dynamic response characteristics and seismic capacity of the reservoir bank slope. Therefore, the degradation law of the dynamic characteristics of the bank slope rock mass should be systematically considered in the analysis and evaluation of long-term seismic performance of reservoir bank slope.

Keywords: water-rock interaction; cyclic loading and unloading; sequential action; dynamic characteristics; damage evolution

1 Introduction

During an earthquake, the most basic phenomenon is continuous ground vibration, which will not only cause damage to buildings or structures, but also cause a large number of secondary disasters such as landslides, avalanches, and ground fractures. These secondary disasters will last for a few to tens of years. In the years after the Wenchuan earthquake in 2008, many geological disasters such as landslides and debris flows occurred in Wenchuan, Dujiangyan, Mianzhu and other places once again attracted great attention[1−2]. The main reason is that the vibration load during the earthquake caused the damage and destruction of the rock matrix structure[3], also known as the "shattered mountain"[1−2]. Although these mountains were not directly damaged during the earthquake, they are likely to develop in an unstable direction under the influence of factors such as rainfall or reservoir water infiltration.

Since the impoundment of the Three Gorges Reservoir area began in 2003, reservoir earthquakes have followed one after another. Up to now, more than 10,000 reservoir earthquakes related to water storage have occurred along the rivers in the reservoir area[4], mainly concentrated below magnitude 4. There were 7 earthquakes with magnitude 4 or higher, and the largest was the magnitude 5.1 earthquake that occurred in Badong County on December 16, 2013. Although these frequent medium/low intensity reservoir earthquakes only caused damage to the buildings on the bank of the reservoir and partial collapse of the slope, the damage effect of vibration loads on rock and soil mass of reservoir bank slope during earthquake can not be ignored according to previous research experience. The slope of the reservoir bank is different from the general engineering slope. In addition to being subjected to various loads, it also has to withstand the impact of the storage operation of the reservoir for a long time.

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During the storage operation of reservoirs, water-rock interactions exist for a long time, which results in the low and medium intensity reservoir earthquakes' frequently occurring

Since the impoundment of the Three Gorges Project, the deterioration of the physical and mechanical properties of the rock and soil caused by the water-rock interaction of the slope of the reservoir has gradually attracted the attention of scholars in related fields. Water-rock interaction tests of sandstone, mudstone, limestone and other types of rocks have been designed and carried out, the damage and degradation equations of various rocks under water-rock interaction have been developed[5–14]. However, these studies mainly focus on the analysis of the influence of water-rock interacttion on rock statics parameters. In recent years, with the frequent occurrence of reservoir earthquakes, many scholars have analyzed and explained the inducing mechanism of reservoir earthquakes[15–19], the correlation between earthquake frequency and the ups and downs of reservoir water level[20]; some scholars have preliminarily analyzed and explained the degradation law of the dynamic characteristics of rocks under the action of water-rock interactions, and found that the dynamic characteristics of sandstone under the interaction between water and rock also have a significant trend of degradation[21–23]. However, there are few studies on the damage and deterioration characteristics of reservoir bank slope rock mass under the coupled action of water-rock interaction and reservoir earthquake. For the slope of the reservoir bank, although the current reservoir earthquake only leads to the partial collapse of some bank slopes, the damage deterioration effect of reservoir slope rock mass and its impact on the long-term stability of the bank slope are worthy of attention under the frequent low and medium intensity reservoir earthquake and long-term water rock interaction.

Previous studies have shown[5–8] that under the effects of periodic fluctuations in the reservoir water level and dry-wet cycles, the damage and deterioration of the rock matrix in the hydro-fluctuation zone directly affect the deformation and stability of the reservoir bank slope. The hydro-fluctuation zone is the key research area. In this study, the water-rock interaction tests were designed to simulate the dynamic damage evolution law of rock mass in the hydro-fluctuation zone. At the same time, in order to simulate the damage effect of low-and medium- intensity reservoir earthquakes on rock samples, the rock samples were cyclically loaded and unloaded in different test cycles to simulate frequent earthquakes, referring to the previous experimental research experiences[21–25]. The analysis of the degradation law of physical and mechanical properties of bank slope rock mass under long-term water-rock interaction and frequent reservoir earthquakes was conducted, which provides a theoretical basis for the dynamic response analysis and safety evaluation of the bank slope.

2 Experimental design and calculation principle

2.1 Sample preparation

The sericite medium-grained quartz sandstone from the bank slope of a reservoir in Shazhenxi Town, Zigui County, Three Gorges Reservoir area was selected as the test object. A standard rock sample of 50 mm (diameter) × 100 mm (height) was prepared in accordance with the specification requirements[26]. Before the test, the samples were screened through ultrasonic testing, quality and geometric size testing, and the rock samples with relatively concentrated wave speed and density ranges were selected as the test rock samples[27]. The typical rock samples are shown in Fig. 1.

Fig. 1 Typical rock sample photos

2.2 Water-rock interaction and seismic process simulation

In order to simulate the reservoir water environment of the hydro-fluctuation zone of reservoir bank slope, YRK-2 rock immersion-air drying tester was developed as shown in Fig.2. It can better simulate the rise and fall of water pressure and immersion-air drying cycle process during the fluctuation of the reservoir water level. With reference to previous experimental experience[6–7], the design of a single water-rock interaction period of 40 d is divided into two stages. The first stage is the air drying stage with low water level (145 m), in which the rock sample is placed in a soaking container, with the temperature controlled at 35 ℃ and air dried for 10 days. The second stage is the rising and falling stage of the reservoir water level, in which the simulated reservoir water level rises from 145 m to 175 m, then remains stable and drops to 145 m. At this stage, the water pressure in the pressure chamber in the first 10 d uniformly increases to 0.3 MPa, and then remains stable for 10 d, and finally uniformly decreases to 0 in the last 10 d. Keep repeating the above-mentioned air drying–soaking and water pressure rising and falling cyclic process, and the design total number of cycles is 10 times. The soaking solution is the reservoir water near the sampling point.

To examine the cumulative damage evolution of the dynamic characteristics of the rock matrix of the reservoir bank slope subjected to frequent, medium- and low-intensity earthquakes as well as periodic water-rock interactions, at initial saturation and after the end of the first, second, fourth, sixth, eighth, and tenth immersion, the uniaxial cyclic loading and unloading test on the same group of rock samples (4 samples, numbered C1-1–C1-4) is carried out repeatedly to simulate the cumulative damage to the rock matrix caused by frequent earthquakes, here called scheme 1 .

Fig. 2 YRK-2 rock immersion–air drying tester

In order to compare and analyze, in the above-mentioned experiments, we carry out the comparative experiments of other two kinds of schemes at the same time, namely scheme 2 and scheme 3. Scheme 2: Take a group of rock samples (4 samples) in different water-rock interaction cycles for uniaxial cyclic loading and unloading tests, focusing on the analysis of the impact of cyclic water-rock interaction on the dynamic characteristics of sandstone. Scheme 3: Before the water-rock interaction test, take a set of rock samples (4) to perform a uniaxial cyclic loading and unloading test to simulate the initial damage effect of the seismic action on the rock matrix of the reservoir bank slope, and then perform periodic water- rock interaction tests. At the same time, we conduct acoustic and porosity tests on rock samples in different water-rock interaction cycles, focusing on the analysis of the degradation laws of rock masses with initial damage under long-term water-rock interactions.

The uniaxial compressive strength of the rock sample in the initial saturated state is about 75 MPa. Previous research results have shown that after 10 immersion–air drying cycles, the strength of the rock sample deteriorates by about 40%[12–13]. After the dynamic damage is superimposed, the degradation amplitude may further increase. At the same time, considering the low seismic intensity of the reservoir in the Three Gorges Reservoir area, in order to ensure that the same cyclic load is applied uniformly in each cycle, referring to previous research experience [21–25], the upper limit of the stress level is set to be 20 MPa in the cyclic loading and unloading tests. In order to ensure a good contact between the sample and the indenter of the testing machine during the unloading process, the lower limit of the stress level applied is set to be 5 MPa. The mechanical test is carried out on the RMT150C rock mechanics testing system. The loading waveform is a sine wave with a frequency of 0.2 Hz. Referring to the previous experience of similar cyclic loading and unloading tests[24–25], the design cyclic loading and unloading is 30 cycles. The uniaxial cyclic loading stress–strain curve of the rock sample is shown in Fig. 3.

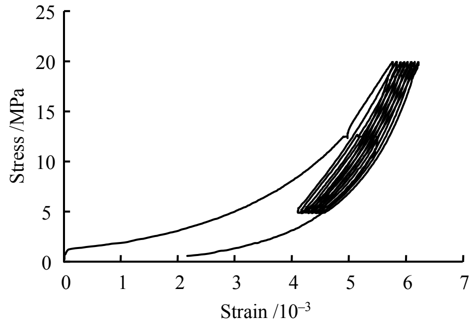


Fig. 3 Stress–strain curve of typical rock sample under cyclic loading and unloading

2.3 Calculation principles of rock dynamic parameters

Rock is not an ideal elastic medium, and contains a large number of small pores, cracks and other flaws. Under the actions of cyclic loading and unloading, the stress–strain curve usually forms a hysteresis curve as shown in Fig. 4. The calculation formulas of related dynamic parameters are [24–25]

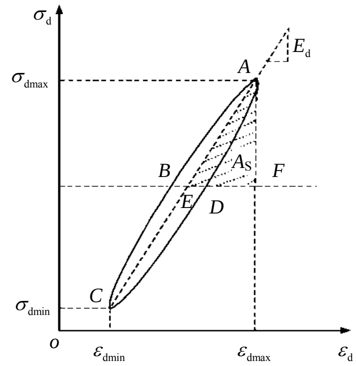


Fig. 4 Stress–strain hysteresis loop curve

$$\lambda = A_R / 4\pi A_S \quad (1)$$

$$C = A_R / \pi X^2 \omega \quad (2)$$

$$E_d = (\sigma_{d\max} - \sigma_{d\min}) / (\varepsilon_{d\max} - \varepsilon_{d\min}) \quad (3)$$

where λ is the damping ratio; C is the damping coefficient (kN·s·mm^{-1}); E_d is the dynamic modulus of elasticity (MPa); A_R is the area enclosed by the *ABCDA* hysteresis curve (kN·mm); A_S is the triangle *AEF* area (kN·mm); X is the dynamic response amplitude (mm); ω is the circular frequency of cyclic loading and unloading (rad/s); σ_{dmin} and σ_{dmax} are the minimum and maximum dynamic stresses of the hysteresis curve, respectively; and ε_{dmin} and ε_{dmax} are the corresponding minimum and maximum dynamic stress strains, respectively.

3 Cumulative damage evolution law of dynamic characteristics

In the test data analysis, in order to facilitate the comparative analysis of the dynamic parameters of rock samples with different water-rock interaction cycles, the hysteresis curve corresponding to the 16th cycle of the 30 cycles of loading and unloading was used to calculate the relevant dynamic parameters. The dynamic parameter change curves of typical rock samples in scheme 1 is illustrated in Fig. 5.

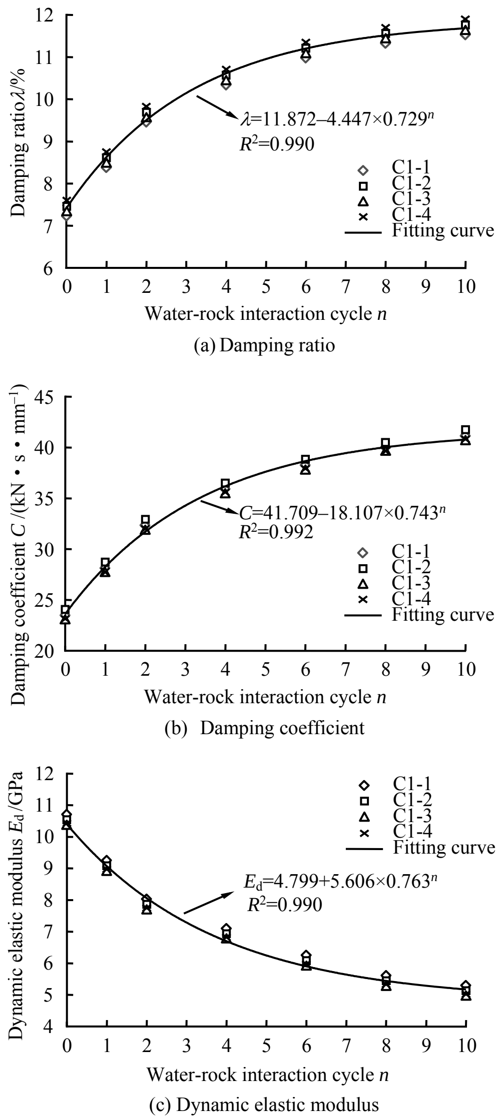


Fig. 5 Variations of dynamic characteristic parameters of sandstone in scheme 1

The results in Fig. 5 show that the dynamic parameters of the sandstone sample have a clear trend. Among them, after 8 water-rock interaction cycles, the damping ratio and damping coefficient of the sandstone have increased by 55.71% and 69.97%, respectively. The elastic modulus decreased by 48.48%; after 10 cycles of water-rock interaction, the damping ratio and damping coefficient increased by 58.42% and 75.30%, respectively, and the dynamic elastic modulus decreased by 51.43%. In comparison, the dynamic characteristic parameters of sandstone in the first eight water-rock interaction cycles have a particularly obvious trend, and then the dynamic parameters tend to be gentle, and the overall change is in the form of an exponential function. During the test, there are also some differences in the amplitude of variation of dynamic parameters of rock samples during the test, which may be related to the morphological changes of hysteresis loop. As the water-rock interaction period increases, the hysteresis loop becomes more and more full and gradually tilts to the right. This is coincident with the law of change obtained in the previous literatures[21−23], and will not be repeated here.

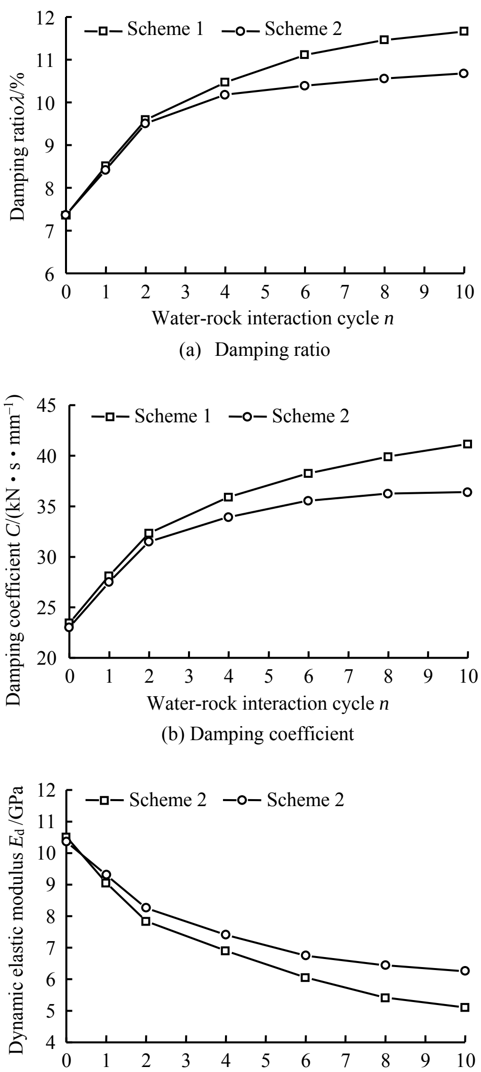
In scheme 2, cyclic loading and unloading tests of the same stress path were carried out on rock samples with different water-rock interaction cycles, and the degradation curve of related dynamic parameters is present in Fig. 6. In order to compare the degradation laws of the dynamic characteristics of the rock samples under the two schemes, the results from scheme 1 are also plotted in Fig. 6

Under the conditions given by scheme 2, the dynamic parameters of the sandstone sample change in the same manner as scheme 1. But there are obvious differences in the range of changes, and as the water-rock interaction cycle number increases, the difference gradually increases. After 4 water-rock interaction cycles, the damping ratio and damping coefficient of the rock sample in scheme 1 increase by 42.26% and 52.98%, and the dynamic elastic modulus decreases by 34.32%. The ranges of changes in the dynamic parameters of the rock sample in scheme 2 are 38.13%, 47.37%, and 28.47%, respectively. The dynamic parameters of the rock samples under the two schemes have little difference. Then, the difference between the two plans gradually increases. After 10 water-rock interaction cycles, the dynamic parameters of the rock sample in scheme 1 change by 58.42%, 75.30%, and 51.43%, respectively, and the dynamic parameters of the rock sample in scheme 2 change. The ranges are 44.91%, 58.10%, and 39.58%, respectively. In comparison, for the first 8 water-rock interaction cycles of scheme 1, and the first 4 water-rock interaction cycles of scheme 2, the dynamic parameters of the rock sample have a particularly obvious deteriorating trend, and then gradually get stabilized. The amplitude of the deterioration of the dynamic parameters of rock samples in scheme 2 is obviously smaller than that of scheme 1, and the deterioration trend reaches a steady state sooner.

Compared with the single periodic water-rock interaction in scheme 2, the dynamic parameters of the rock samples in scheme 1 deteriorate more significantly under the sequential action of water-rock interaction and cyclic loading and unloading. This implies that under the long-term water-rock interaction, even if the dynamic load with a small amplitude is superimposed, it also will exacerbate the damage effect of rock mass in the hydro-fluctuation zone gradually.

4 Deterioration mechanism

In order to better analyze the damage and degradation mechanism of sandstone dynamic characteristics under the sequential actions of periodic water-rock interaction and cyclic loading and unloading, some testing and analysis were made as follows. The longitudinal wave velocity and porosity of sandstone specimens under the three schemes was determined in different water-rock interaction cycles. SEM micro-scanning analysis was performed on the rock samples for the three schemes after 10 water-rock interaction cycles.



(a) Damping ratio

(b) Damping coefficient

(c) Dynamic elastic modulus

Fig. 6 Variations of dynamic characteristic parameters of sandstone in schemes 1 and 2

4.1 Longitudinal wave velocity and secondary porosity of rock samples

During the process of water-rock interaction, the pores and fissures inside the rock sample gradually develop, resulting in a gradual decrease in the integrity of rock. According to the evaluation index of rock mass integrity in "*Standard for engineering classification of rock mass*" (GB/T 50218-2014)[28], the integrity degradation coefficient of the rock sample under water-rock actions is specifically defined as

$$K'_{\mathrm{V}} = (V_{\mathrm{i}} / V_0)^2 \tag{4}$$

where V_0 is the longitudinal wave velocity of the rock sample before the water-rock interaction; V_{i} is the longitudinal wave velocity of the rock sample subjected to different water-rock interaction cycles; K'_{V} is the integrity deterioration coefficient of the rock sample, the integrity deterioration coefficient in the initial state is 1.0. The integrity deterioration coefficients of rock samples with different water-rock interaction cycles reflect the development degree of pores and fissures in the rock samples. The analysis shows that the change curves of the integrity deterioration coefficient of the rock samples under the three schemes is illustrated in Fig. 7.

In order to compare and analyze the porosity changes of the three types of rock samples during the water-rock interactions, the variations of secondary porosity of the rock samples under the three scenarios are shown in Fig. 8.

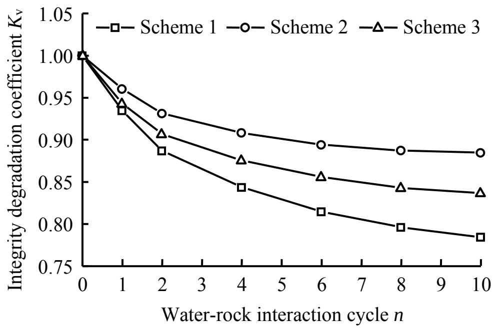


Fig. 7 Integrity degradation coefficients of rock samples under three schemes

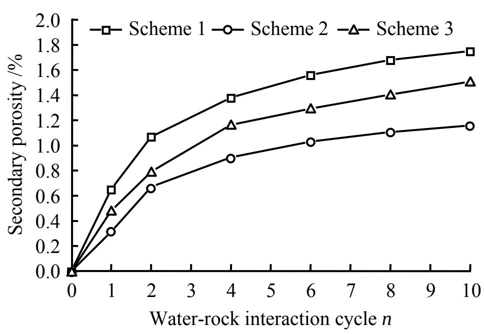


Fig. 8 Secondary porosities of rock samples under three schemes

It can be observed from Fig. 7 and Fig. 8:

(1) Under the three schemes, the integrity deterioration coefficient of the rock sample shows a significant decreasing trend, and the overall change laws are consistent. But there is a big difference in the change range. In comparison, the reduction of the integrity deterioration coefficient of the rock sample under the

periodic water-rock interaction in scheme 2 is the smallest, and it is mainly concentrated in the first 4 water-rock interaction cycles, and the integrity deterioration coefficient is reduced to 0.91. Under the 10 times water-rock interaction, the integrity deterioration coefficient is reduced to 0.88 after the action period. Scheme 3 considers damage to rock caused by initial earthquake, so the coefficient of integrity deterioration of rock samples decreases greatly, mainly in the first 6 water-rock interaction cycles, the coefficient of integrity deterioration falls to 0.86, and after 10 water-rock interaction cycles, the coefficient of integrity deterioration reduces to 0.84. In scheme 1, the integrity deterioration coefficient of the rock sample decreases the most under the sequential action of the cyclic water-rock and cyclic loading and unloading, and the reduction trend is obvious in the first 8 water-rock interactions, and the integrity deterioration coefficient decreases to 0.80 while after 10 water-rock interaction cycles, the integrity deterioration coefficient declines to 0.78.

(2) Under the three schemes, the secondary porosity of the rock samples grows firstly steeply and then slowly, and there are obvious differences in the variation range of each scheme, which is consistent with the change trend of the integrity deterioration coefficient of the rock samples. Among them, the secondary porosity increase of the rock samples in scheme 2 is the smallest, and it is mainly concentrated in the first 4 water-rock interaction cycles, which is 0.91%. After 10 water-rock interaction cycles, the secondary porosity is 1.16%. Scheme 3 considers damage by the initial seismic action to the rock sample, the secondary porosity has a large increase, and the secondary porosity of the first 6 water-rock interaction cycles increases rapidly, which is 1.29%; after 10 water-rock interaction cycles, the secondary porosity reaches 1.51%. Due to the sequential action of the cyclical water-rock and cyclic loading and unloading in scheme 1, the secondary porosity of the rock sample increases the most, and the secondary porosity of the first 8 water-rock interaction cycles increases significantly to 1.68%; after 10 cycles of water-rock interaction, the secondary porosity runs up to 1.75%.

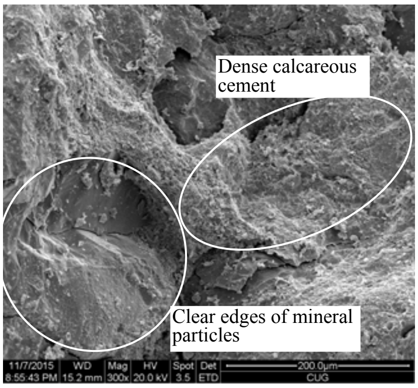
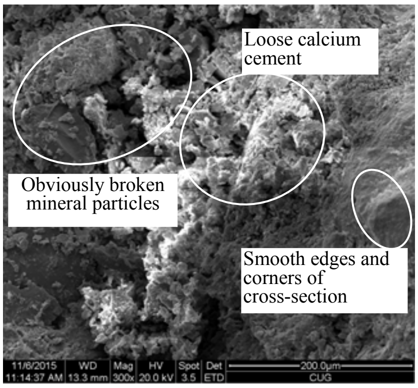
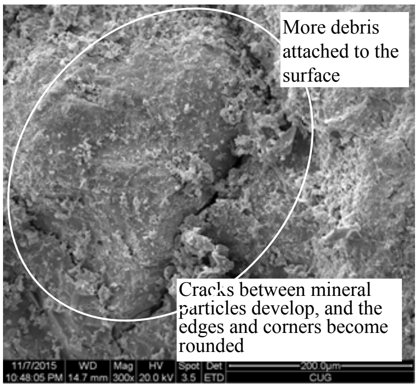
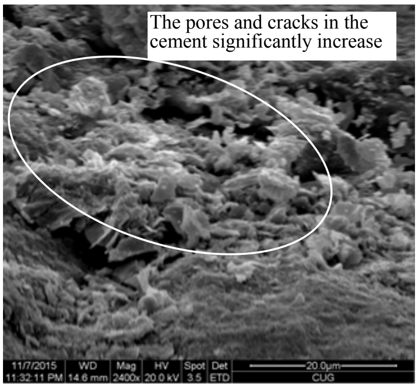
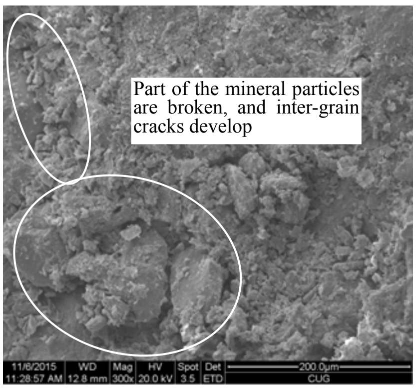
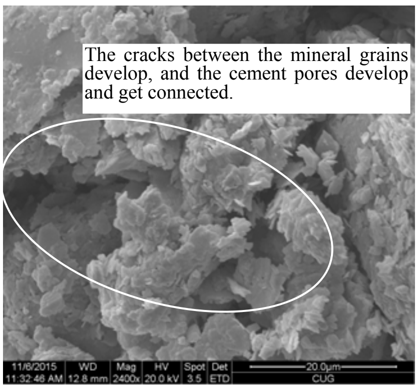
(3) Variation trends of the longitudinal wave velocity and secondary porosity of the sandstone sample during the water-rock interaction are accordant with that of aforementioned dynamic parameters. In scheme 2 the rock sample is mainly damaged by periodic water-rock interactions, thus the variation ranges of the longitudinal wave velocity and secondary porosity of the rock sample are relatively small. Scheme 3 is mainly aimed at investigating the cyclic loading and unloading damage of bank slope rock mass caused by earthquake action. The rock samples have been damaged by the initial dynamic action to a certain extent before the water-rock interactions. Therefore, in the same water-rock interaction cycle, the variation amplitudes of secondary porosity and the longitudinal wave velocity of the rock sample are greater than that of scheme 2. The influences of seismic action and water rock action are considered in scheme 1. Under the cyclic water-rock and cyclic loading and unloading, the damage caused by water-rock action and the damage caused by the cyclic loading and unloading are accumulated constantly, which result in the variations of longitudinal wave velocity and secondary porosity of rock samples more significant; and then this change gradually stabilizes after the samples experience more water-rock interaction cycles.

4.2 Variation characteristics of microstructure

In order to examine the influence of water-rock interactions and cyclic loading and unloading on the microstructure of rock samples, the initial state and typical SEM photos of the rock samples after 10 water-rock interaction cycles are provided in Table 1.

Table 1 shows that in the initial state, the mineral grain structure of the rock sample is dense, the bond between the grains is tight, and only some tiny pores and cracks occur at the edges of the mineral grains and in cement. After 10 cycles of water-rock interactions, the microscopic structure of the rock sample has changed significantly. The outline of mineral grains gradually tends to be smooth, and the obvious corrosion pits are found to appear on grain surface attached by secondary minerals and lithic fragments; the dissolution and corrosion of calcareous cement are observed more clearly, and its structure is loose, and the cracks are developed and coalesced. In comparison, the changes in the microscopic structure of the rock samples in scheme 2 are mainly represented by dissolution and corrosion of calcareous cements, development of pore and fissure in cements. In scheme 3 the initial cyclic loading and unloading of rock samples leads to the breakage of some mineral particles and the development of cracks between particles. As a result, the rock samples contain the initial damage, which obviously intensifies the dissolution of cement between mineral particles under water-rock interaction cycles. In scheme 1 under the sequential actions of water-rock interaction and cyclic loading and unloading, the mineral particles are broken more obviously; the cracks between the particles develop and converge in multiple directions, and the cement is porous and loose, indicating that the periodic water-rock and cyclic loading and unloading sequences promote the accumulation and development of microstructure damage in the rock sample. In general, in the three schemes, the change characteristics of the pore and crack structures shown in the SEM scanning photos of the rock sample are consistent with increase trend of the aforementioned statistical secondary porosity.

Table 1 Characteristics of micro-structure changes of sandstone samples under three schemes

<table>
<tr><th>Sample status</th><th colspan="2">SEM photo of typical rock sample</th><th>Characteristics changes</th></tr>
<tr><td>Initial status</td><td>
</td><td>
</td><td>The mineral particles are tightly wrapped by the cement, and the calcareous cement is dense, with some tiny pores and cracks.</td></tr>
<tr><td>Scheme 1</td><td>
</td><td>
</td><td>The mineral particles are broken obviously, the edges and corners become gradually rounded, and the surface of the particles is attached with lithic fragments and secondary minerals; the calcareous cement between the particles is loose, its pores are significantly developed and are partially coalesced, and the pore size becomes noticeably larger.</td></tr>
<tr><td>Scheme 2</td><td>
</td><td>
</td><td>The edges of mineral grains gradually become smooth, obvious pits are observed on the surface of the grains, the surface of the particles is attached by lithic fragments; the cement between the mineral grains dissolves obviously, cracks gradually develop and gather, and the pores increase insignificantly.</td></tr>
<tr><td>Scheme 3</td><td>
</td><td>
</td><td>Part of the mineral particles have decomposed and broken, and there are many pits on the surface of the mineral particles, and the particle surface is attached by more rock debris; the cements between the mineral particles have dissolved obviously, the pores between the particles gradually gathering and the cracks are gradually coalescing.</td></tr>
</table>

4.3 Cumulative damage evolution mechanism

The rock sample used in the test is calcareous sandstone with porous calcareous cementation. In the process of water-rock interactions, on the one hand, the skeleton of mineral particles is softened due to the action of water; on the other hand, physical and chemical interactions occur between water and calcareous cements in rock samples, resulting in the generation of some secondary minerals [29-30]; and under the action of the fluctuation of water pressure and the immersion–air drying cycle, the microscopic pores and cracks inside the rock sample gradually develop and coalesce, leading to the deterioration of the dynamic properties of the rock sample. From the statistical results of the aforementioned rock sample dynamic parameters, SEM scanning and secondary porosity, it can also be found that the physical and mechanical parameters of the rock sample in scheme 2 have the smallest change range, followed by scheme 3, and scheme 1 has the largest change. The main reason is inferred that the test object of scheme 2 is a complete rock sample, with relatively few internal pores and cracks, less infiltrating paths and spaces for reservoir water, and smaller space for water-rock interaction, which results in the deterioration rate and amplitude of dynamic properties small. The test object in scheme 3 is the rock sample that has undergone cyclic loading and unloading. The cyclic loading and unloading action causes a certain initial damage to the rock sample. The newly increased microscopic pores and fissures inside the rock sample provide more reaction space and surface area for water-rock interaction. Thus, the process of water-rock interaction is relatively fast, and the physical and mechanical properties of corresponding rock samples deteriorate at a relatively fast rate and with a large amplitude. In scheme 1, the rock samples undergo cyclic loading and unloading in each water-rock interaction cycle. The crushing of mineral particles, the dislocation of the cement between particles, and the gradual accumulation of shear failure, continue to provide new reaction space and surface for water-rock interaction, and accelerate the process of water-rock interaction, leading to rapid and large deterioration of the physical and mechanical parameters of the rock sample.

5 Conclusion and discussion

(1) Under the water-rock interactions, the dynamic characteristics of the rock sample have a significant deteriorating trend, and the overall trend is that it changes sharply first and then slowly. The deterioration rate and trend of dynamic parameters of rock samples are significantly increased after superimposition of seismic action into water-rock interaction. It indicates that there is obvious cumulative damage evolution trend in rock mass of reservoir bank slope under long-term water-rock interaction and frequent moderate-low intensity earthquakes.

(2) Under the sequential actions of water-rock interaction and cyclic loading and unloading, the microscopic structure of the rock sample has an obvious deterioration trend, and the integrity coefficient and the secondary porosity of the rock sample show a trend of first steep and then slow change according to statistics. In comparison, the microstructure changes of rock samples under the sequential actions of water-rock interaction and cyclic loading and unloading are the most significant, followed by the rock samples with initial cyclic loading and unloading damage, and the change trend of rock samples under the action of water-rock alone is the smallest. The changes and differences of the microscopic structure of the rock sample under different schemes also determine the deterioration law of its dynamic characteristics.

(3) After reservoir impounding operation, long-term water-rock interaction and frequent reservoir earthquakes will lead to cumulative development of rock mass damage in the hydro-fluctuation belt of reservoir bank slope, and the dynamic response characteristics and seismic resistance of reservoir bank slope will gradually deteriorate. Therefore, in the analysis of long-term seismic performance of reservoir bank slope, it is necessary to systematically consider the deterioration laws of dynamic characteristics of bank slope rock mass.

References

[1] XU Qiang. Main types and characteristics of the geo-hazards triggered by the wenchuan earthquake[J]. Journal of Geological Hazards and Environment Preservation, 2009, 20(2): 86–93.

[2] ZHU Xing-hua, CUI Peng, GE Yong-gang. Numerical simulation of flow and sediment transport in the early stage of Three Gorges Reservoir operation[J]. Journal of Yangtze River Scientific Research Institute, 2012, 2(1): 1–6.

[3] HU Zhi-qi, ZHENG Wen-heng, LU Ming-yong. Preliminary study of crustal stress and its effect on earthquake triggering[J]. Journal of Geodesy and Geodynamics, 2005, 25(1): 108–112.

[4] CHEN Jun-hua, GAN Jia-si, LI Sheng-le, et al. Seismic activity characteristics in Dongrangkou area, Badong county of Hubei province[J]. Journal of Geodesy and Geodynamics, 2007, 27(3): 97–105.

[5] LIU Xin-rong, FU Yan, WANG Yong-xin, et al. Deterioration rules of shear strength of sand rock under water-rock interaction of reservoir[J]. Chinese Journal of Geotechnical Engineering, 2008, 30(9): 1298–1302.

[6] DENG H, YUAN X, WANG L, et al. Experimental research on changes in the mechanical property law of reservoir bank sandstone under “immersion-air dry” circulation[J]. Environmental Engineering and Management Journal, 2013, 12(9): 1785–1789.

[7] DENG H F, ZHOU M L, LI J L, et al. Creep degradation mechanism by water-rock interaction in the red-layer soft rock[J]. Arabian Journal of Geosciences, 2016, 9(12): 1–12.

[8] ZHANG Zhen-hua, WANG Ye. Degradation mechanism of shear strength and compressive strength of red sandstone in drawdown areas during reservoir operation[J].

Chinese Journal of Geotechnical Engineering, 2019, 41(7): 1217–1226.

[9] HALE P A, SHAKOOR A. A laboratory investigation of the effects of cyclic heating and cooling, wetting and drying, and freezing and thawing on the compressive strength of selected sandstones[J]. Environmental and Engineering Geoscience, 2003, 9(2): 117–130.

[10] CARMINE APOLLARO, LUIGI MARINI, TERESA CRITELLI, et al. The standard thermodynamic properties of vermiculites and prediction of their occurrence during water-rock interaction[J] Applied Geochemistry, 2013, 35: 264–278.

[11] TALLINI MARCO, PARISSE BARBARA, PETITTA MARCO, et al. Long-term spatio-temporal hydro chemical and Rn-222 tracing to investigate groundwater flow and water-rock interaction in the Gran Sasso (central Italy) carbonate aquifer[J]. Hydrogeology Journal, 2013, 21(7): 1447–1467.

[12] ALT-EPPING, DIAMOND L W, HARING M O, et al. Prediction of water-rock interaction and porosity evolution in a granitoid-hosted enhanced geothermal system, using constraints from the 5 km Basel-1 well[J]. Applied Geochemistry, 2013, 38: 121–133.

[13] HUROWITZ JOEL A, FISCHER WOODWARD W. Contrasting styles of water-rock interaction at the Mars Exploration Rover landing sites[J]. Geochimica et Cosmochimica Acta, 2014, 127: 25–38.

[14] HUANG Zhi-gang, ZUO Qing-jun, WU Li, et al. Nonlinear softening mechanism of argillaceous slate under water-rock interaction[J]. Rock and Soil Mechanics, 2020, 41(9): 2931–2942.

[15] CHEN Shu-jun, SU Ai-jun, LUO Den-gui. Genesis and type of induced earthquake in Three Gorges Reservoir[J]. Journal of Geodesy and Geodynamics, 2004, 24(21): 70–73.

[16] HAN Xiao-guang, RAO Yang-yu. Analysis of genesis of reservoir-induced microquakes in Badong reach of Three Gorges[J]. Journal of Geodesy and Geodynamics, 2004, 24(2): 74–77.

[17] LI Feng, HAN Xiao-yu, DAN Wei, et al. Analysis of seismicity in Badong area of Three Gorges Reservoir[J]. Journal of Geodesy and Geodynamics, 2008, 28(4): 63–67.

[18] WANG Qiu-liang, ZHANG Li-fen, LIAO Wu-lin, et al. Fault tectonics and seismic activity characteristics of Three Gorges Reservoir[J]. Journal of Geodesy and Geodynamics, 2013, 3(5): 29–33.

[19] CHEN De-ji, WANG Yong-xi, ZENG Xin-ping. A study of reservoir-induced earthquake of Three Gorges Project[J]. Chinese Journal of Rock Mechanics and Engineering, 2008, 27(8): 1513–1524.

[20] MA Wen-tao, XU Chang-peng, LI Hai-ou, et al. Intensive observation of reservoir-induced earthquake and preliminary analysis on the causes of earthquakes in Three Gorges Reservoir[J]. Seismology and Geology, 2010, 32(4): 552–563.

[21] ZHANG Yin-chai. Study on dynamic response characteristics of reservoir bank slope under the influence of reservoir earthquake and water-rock interaction[D]. Yichang: China Three Gorges University, 2019.

[22] ZHANG Yin-chai, DENG Hua-feng, WANG Wei, et al. The dynamic response law of bank slope under water-rock interaction[J]. Advances in Civil Engineering, 2018(8): 1–10.

[23] DENG Hua-feng, ZHANG Yin-chai, ZHI Yong-yan, et al. Sandstone dynamical characteristics influenced by water-rock interaction of bank slope[J]. Advances in Civil Engineering, 2019 (3): 1–11.

[24] LIU Jian-feng, XU Jin, LI Qing-song, et al. Experimental research on damping parameters of rock under cyclic loading[J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29(5): 1036–1041.

[25] ZHU Ming-li, ZHU Zhen-de, LI Gang, et al. Experimental study of dynamic characteristics of granite under cyclic loading[J]. Chinese Journal of Rock Mechanics and Engineering, 2009, 28(12): 2520–2526.

[26] China Electricity Council. GB/T 50266－2013 Standard for tests method of engineering rock masses[S]. Beijing: China Planning Press, 2013.

[27] DENG Hua-feng, ZHANG Heng-bin, LI Jian-lin, et al. Effect of water-rock interaction on unloading mechanical properties and microstructure of sandstone[J]. Rock and Soil Mechanics, 2018, 39(7): 2344–2352.

[28] The Ministry of Water Resources of People's Republic of China. GB/T 50218－2014 Standard for engineering classification of rock mass[S]. Beijing: China Planning Press, 2015.

[29] DENG Hua-feng, ZHI Yong-yan, DUAN Ling-ling, et al. Mechanical properties of sandstone and damage evolution of microstructure under water-rock interaction[J]. Rock and Soil Mechanics, 2019, 40(9): 3447–3456.

[30] LI Wen-guo, ZHANG Xiao-peng, ZHONG Yu-mei. Formation mechanism of secondary dissolved pores in arose[J]. Oil & Gas Geology, 2005, 26(2): 220–223.